GEOLOGY AND GEOMORPHOLOGY OF THE LADY JULIA PERCY ISLAND VOLCANO, A LATE MIOCENE SUBMARINE AND SUBAERIAL VOLCANO OFF THE COAST OF VICTORIA, AUSTRALIA.

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Lady Julia Percy Island is an intraplate, offshore volcano near Port Fairy in southwestern Victoria. The island is about seven million years old. Early volcanic activity formed a subaqueous edifice of pillow lava and associated hyaloclastite, above which lies a pahoehoe flow. Subsequent subaerial eruptions produced pyroclastic flows, plains-type lava flows and scoria deposits. Lava flow features which are the best preserved examples of their type in Victoria include pillows with multiple crusts and hollow tubes, hyaloclastite, pahoehoe flows with ropy and spongy lava textures and gas-formed canals. Extensive erosion has exposed much of the internal structure of the volcano, including a volcanic vent at Pinnacle Point. The steep and near-continuous coastal cliffs preserve numerous different ancient sea level markers as wave-cut platforms, sea caves, a stranded boulder beach, and the transition from subaqueous to subaerial lava textures. Ancient wave-cut platforms also occur beneath present sea level. Bulk rock major and minor element variation indicate that all the lavas of the island belong to the same source, are not highly fractionated, and ascended rapidly through the crust to the surface. They have alkaline compositions that closely resemble that of typical ocean island basalt.

Key words: Lady Julia Percy Island, Newer Volcanics, radiometric dating, Miocene, submarine volcanism, pillow lava, hyaloclastite, geochemistry, volcanic textures, palaeo-sealevels, neotectonics

LADY Julia Percy Island lies approximately 22km southwest of Port Fairy, 4km off the coast of southwestern Victoria, Australia (Fig. 1). The ocean setting of this volcano provides excellent rock exposures as coastal cliffs, which expose the internal structure of the volcano and one of its vents. Continued rapid erosion maintains clean cliff faces, which reveal primary volcanic features rarely well exposed in the rock record. In particular, the island provides some of the best insights available in Australia into the processes leading to the formation of pillow lavas and hyaloclastite, pyroclastic flows and pahoehoe lavas. The detailed description of the characteristics of the myriad of well preserved diagnostic primary volcanic features at Lady Julia Percy Island presented here—particularly the pillow lavas and associated hyaloclastite deposits—will aid in the recognition and interpretation of similar features in the local Recent and ancient rock records.

This paper describes the geology of the island, presents new K/Ar radiometric age data, reconstructs a possible eruption history, and also documents geomorphological features related to past sea levels. A brief social history of the island is also presented.

HISTORY

Aboriginal history

The Gunditjmara people of southwestern Victoria referred to Lady Julia Percy Island as Deen Maar (Dawson 1881) or Dhinmar (Matthew 1904), and considered it to have spiritual significance. Their dead were wrapped in grass and buried with their heads directed towards the island so that their spirits could be lifted to the clouds (Dawson 1881) or spirited to the island to await reincarnation (Matthew 1904). The discovery of sharp chert blades and possible grinding tools (Gill & West 1971) suggests that aboriginal people visited the island, presumably either by braving the rough sea and dangerous landing in locally made canoes, or by walking from the main-

Fig. 1. Locality map.

land during periods of lower sea level. Local indigenous ethnohistory is documented by Debney & Cekalovic (2001).

European discovery

In 1800 Lieutenant James Grant, commander of the surveying vessel H.M. Lady Nelson, became the first European explorer to sail through the strait between New Holland and Van Dieman's Land. On December 6th he noted a "...large, inaccessible island off the S.E. coast of New Holland...". This he named Lady Julian's Island, in honour of Lady Julian Peircy. However, the name recorded on his chart is Lady Julia Percy's Is, the name adopted in 1802 by Matthew Flinders who produced a more accurate chart of Terra Australis. Also in 1802, Nicholas Baudin, commander of the French ship 'Le Geographe', (re)discovered "a small island off Cape Reamur" (Grant's Lady Julian's Island) which he named Isle Fourcroy (Learmonth 1934). In 1836 Major Mitchell sighted a large island from the Portland Bay district, and concluded it was "one of the Lady Julia Percy's Isles" (Learmonth 1934). Modern maps refer to the island as Lady Julia Percy Island (Department of Crown Lands and Survey 1982). In 1840 a trigonometrical station was established on the island as the western point in a survey of the Victorian coast between Melbourne and the Glenelg River, followed by a second station in 1863 (McCoy Society 1936).

The island's resources have been exploited in various ways. As early as 1798 the Chinese were slaughtering seals off several Victorian islands, including Lady Julia Percy Island, and by the mid-1800s the seal colonies had all but disappeared (Learmonth 1934). Prior to 1876 a small cave deposit of guano at Seal Bay (then referred to as Sealers Cove) was mined, and in 1868 rabbits and guinea fowl were introduced as a food source for shipwrecked sailors. An emergency station for castaways was also established. Between 1879 and 1908 various applicants were granted grazing licences for pigs, cattle and horses on the island (McCoy Society 1936). Now protected as a fauna and flora reserve, the island is listed on the Register of National Estates, and the seal colony has re-established to become one of Victoria's largest.

Previous work

Pioneer work on Lady Julia Percy Island was carried out during the McCoy Society expedition of 1935–1936. The island was surveyed, and the geology and petrology of the island rocks briefly described (McCoy Society 1936). Two Australites were found on the island. Several ecological expeditions visited the island between 1948–1963 (Pescott 1965). The Geological Society of Australia lists the island as a geological monument of national significance (King 1988), although no detailed geological work was undertaken until 1994 (Edwards 1994).

REGIONAL SETTING

Lady Julia Percy Island lies within the Tyrendarra Embayment of the Otway Basin—a type example of a passive, continental margin basin (Falvey 1974), formed by rifting between Australia and Antarctica (Weissel & Hayes 1972). Extensive Cainozoic volcanism in this region forms the Western District Volcanic Plain of southwestern Victoria (Hills 1940), and represents intraplate activity immediately adjacent to the extensional continental margin.

Literature documenting the characteristics of east Australian volcanism has been well summarised and discussed by Johnson (1989) and Price (et al. 2003). In Victoria, Cainozoic volcanics are subdivided on the basis of both geographic distribution and age. Lady Julia Percy Island lies within the Western Dis-

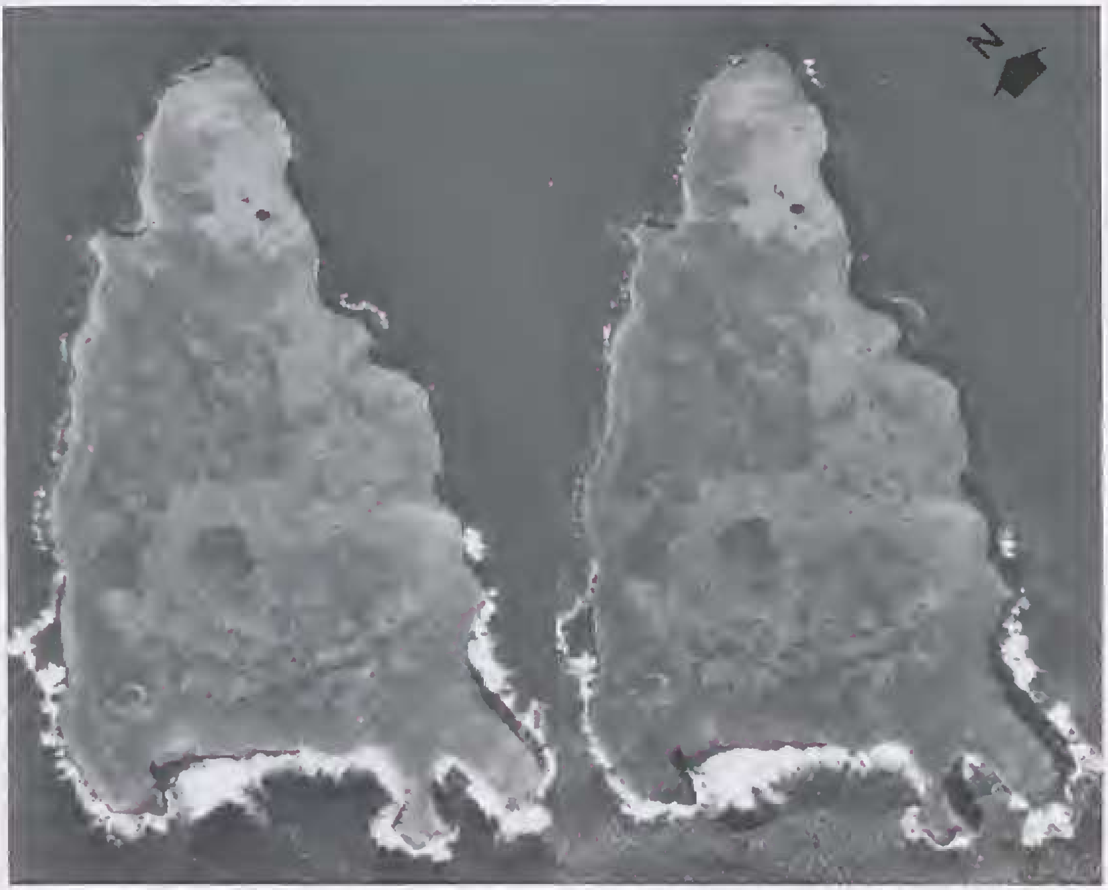


Fig. 2. Stereographic air-photos, Lady Julia Percy Island. The remnants of a vent are exposed in the cliffs of the goose-necked promontory of Pinnacle Point (bottom-right), the highest point on the island at 46m. This point is separated from Thunder Point (bottom-right) by Horseshoe Bay, a deeply-incised cove. The prominent palaeo-wave-cut McCoy Platform (bottom-left) lies just west of Seal Bay. Dinghy Cove, the usual access to the flat plateau on the island, is the sheltered bay at top-left.

trict Province (Price et al. 2003) and is amongst the southernmost Newer Volcanic eruption points in western Victoria. The Victorian Newer Volcanic series, together with the western lava fields of northern Queensland, are the youngest and most extensive lavas in Australia (Nicholls & Joyce 1989). In Victoria they are mostly plains basalt lavas which are predominantly subalkaline to mildly alkaline, and include olivine basalt and minor amounts of tholeiite, basanite, hawaiite and olivine nephelinite (Irving & Green 1976).

The most significant subaqueous volcanic deposits of the province include pillow lava which formed in a lake at Exford South (Condon 1951), and exposures of pillow lava and hyaloclastite at Lady Julia Percy Island. The Newer Volcanic province as a whole has been active since the Late Miocene (Aziz-Ur-Rahman & McDougall 1972), and several eruptions have occurred since Aboriginal occupation. The most recent dated event is 4900 years ago (thermoluminescence age obtained for baked sand beneath lava at Mount Schank; Smith & Prescott 1987).

PHYSIOGRAPHY

Lady Julia Percy Island represents the eroded remains of an offshore, volcanic edifice that rests upon Miocene Port Campbell Limestone. Airborne magnetic data (Geological Survey of Victoria 1999) show that this volcanic sequence is not, and has never been, joined to the mainland by a lava flow.

The island's surface is essentially a flat plateau covering approximately 129ha (Norman et al. 1980). It rises gently towards the southwest, from an elevation of about 30m at Dinghy Cove, to 46m on the remnant of a small volcanic cone at Pinnacle Point. The top of the plateau reflects the upper surface of essentially flat-lying lava flows. A slight (<1m high) rise just north of, and parallel to, the 35m contour represents the flow edge of the youngest lava flow (Fig. 2). Bathymetric data (Fig. 3) suggests that the island once covered an area at least twice as large as present, but has been significantly shortened from the south and southwest by wave erosion.

There is no permanent fresh water on the island. Rainwater collects in several small, shallow ephemeral swamps and pours over the cliffs into the sea, or percolates through joints in the upper lava flows to emerge as springs in the cliff faces. The most prominent spring, The Drip, trickles across the entrances of Fern and Seal caves at the back of Seal Bay.

Regolith

The plateau soils of Lady Julia Percy Island have been described by Edmonds (McCoy Society 1936). The acidic (pH 4.8–6.7) loam soil is generally less than 500 mm deep and contains volcanic rock fragments and limonitic pisolites. It is mostly derived from the *in situ* alteration of the upper lava flows. Basalt gravels occur towards the centre of the plateau. Two low-lying aeolian dunes along the southern edge of the plateau are composed of mafic mineral crystals derived exclusively from the lavas.

GEOLOGY

The Lady Julia Percy Island lavas are fine grained rocks with a groundmass of plagioclase, augite, olivine and accessory magnetite, with microphenocrysts of olivine and plagioclase. Edwards (1994) provides a detailed discussion of the petrography and geochemistry of these lavas, and selected total rock analyses are given in Appendix 1. Major element geochemistry shows that they are weakly fractionated alkali basalts that closely resemble typical OIB compositions. Such lavas are relatively rare in southwestern Victoria, as most alkaline Newer Volcanic rocks are basanitic scoria and pyroclastic deposits (Johnson 1989). Minor and trace element data indicate that the Lady Julia Percy Island lavas have not undergone significant amounts of crustal contamination, and have probably ascended rapidly through the crust to the surface. A lack of variation in the geochemistry between the lavas indicates that they probably shared a similar magma source. These lavas do contain anomalously high lead concentrations, but this is typical of many basaltic lavas and granitic rocks of western Victoria, and reflects a lead-enriched mantle source beneath the province (Hergt et al. 1991; White pers comm. 1994).

Lady Julia Percy Island preserves evidence of two distinct phases of volcanic activity (Figs 4 & 5):

- initial quiet effusion of basaltic lava which formed a subaqueous volcanic edifice, composed predominantly of pillow lava and hyaloclastite, capped by a thin subaerial pahoehoe flow, and
- later subaerially erupted pyroclastic flows, plains-type lava flows, scoria and vitric ash deposits.

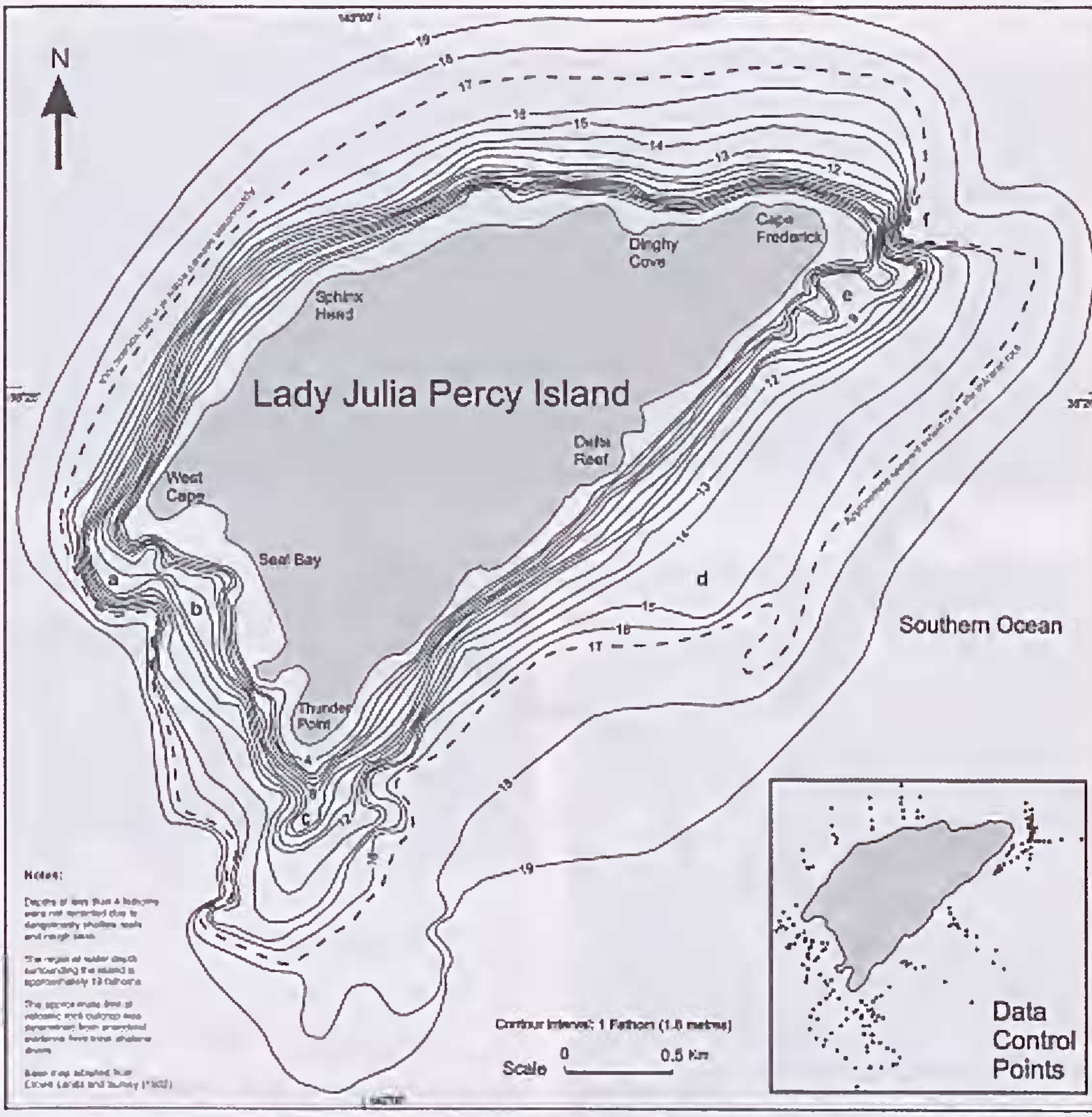


Fig 3. This bathymetric map highlights the formation of the present Lady Julia Percy Island due to differential modification of the original volcanic delta. The northern edge of the seamount rises consistently and moderately steeply from the sea floor. In contrast the southern edge has been more greatly modified by prevailing southwesterly weather systems. Geomorphic features near West Cape (a), Seal Bay (b), Thunder Point (c) and Delta Reef (d) are interpreted to be submerged wave-cut platforms. The submerged bench and steep slope east of Cape Frederick (e and f) are more sheltered and may therefore be primary volcanic features.

These two volcanic episodes were sourced from different vents, and radiometric dating presented below shows that they occurred approximately 1.6 million years apart.

First phase of volcanism

Initial volcanism produced a subaqueous volcanic delta composed predominantly of basaltic pillow lava with associated hyaloclastite and an overlying subaerial pahoehoe flow. Only a small portion of the original seamount remains as Lady Julia Percy Island, but the exposed volcanic features are among the best preserved in Australia.

Pillow lavas. Today the pillow lavas extend from the sea floor to 5m above sea level in the southwest, to a maximum of 15m above sea level at Dinghy Cove.

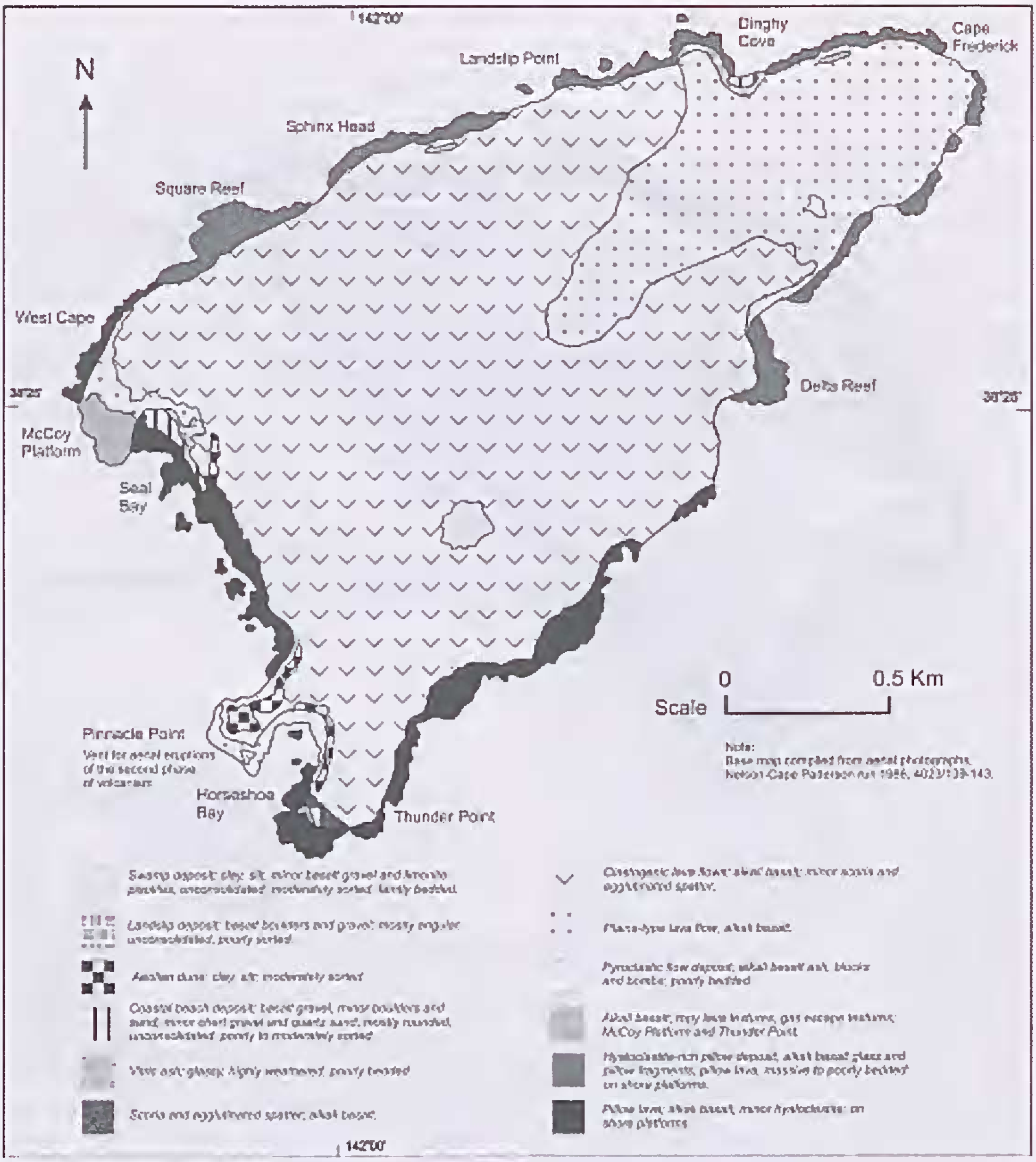


Fig. 4. Geology of Lady Julia Percy Island.

South of Square Reef and Delta Reef the volcanic succession is comprised of an almost solid mass of interlocking pillows, while to the north, pillows are intimately associated with hyaloclastite (Fig. 6). Minor thinly bedded volcanic gravel also occurs between pillows at Seal Bay and McCoy Platform. At Pinnacle Point the deposit is intruded by the vent of younger subaerial eruptions.

The dip direction and amplitude of pillows is highly inconsistent. Subvertical pillows are exposed at Seal Bay and horizontal pillow masses form the surface of small shore platforms between Square Reef and Landslip Point. The majority of pillows however, dip to the north and northwest at 15°–30° (Fig. 5). This preserves the approximate angle and direction of the original flow front which grew from a

Fig. 5. NW view of the southern coastline between Delta Reef and Cape Frederick. North-dipping submarine pillow lavas and associated hyaloclastite deposits are capped by flat-lying subaerially-erupted plains-type lava flows.

Fig. 6. A: Solid pillow mass at Square Reef. These classically shaped pillows have convex upper surfaces and bases that are moulded to the shapes of underlying pillows. Note the ubiquitous radial jointing. The transition into the overlying flat sheets of subaerial plains-type lava flows occurs at 12m above sea level.

B: View of the western headland of Dinghy Cove. Entwined pillows intimately associated with hyaloclastite. Note radial jointing and the well defined chilled crust in the upper pillow (clearest near hammer pick), and spreading cracks and blocky surface texture of the lower pillow.

submerged vent south of the island (see *Pahoehoe flow* for discussion on geopetal surfaces and tilting of island).

Pillow morphology is extremely varied. The true length of pillows is obscured by other pillows or hyaloclastite, but several at Cape Frederick can be traced for at least 40m. In plan, pillows are mostly sinuous and interlocking with neighbouring pillows (Fig. 6). They range from 200mm to approximately 1.5m in diameter, and in cross-section range from spherical to flattened ellipses. Most spherical pillows are completely surrounded by hyaloclastite which provided lateral support as they cooled (Snyder & Fraser 1963). Where individual pillows lie directly upon others they have convex upper surfaces, but their bases are moulded to the rounded surface of underlying pillows (Fig. 6), indicating that when emplaced they were sufficiently fluid to deform (Henderson 1953).

Most pillows are heavily jointed and cracked. Radial cooling joints are virtually ubiquitous. Narrow cracks (≤10mm) perpendicular to the long axis of a pillow formed as the pillows propagated forward. Other cracks in the chilled crust accommodated changes in the direction or dip of the slope over which the pillow flowed, forming in the same manner as crevasses in a moving glacier. Longitudinal and transverse spreading cracks are also common (Fig. 7). These are 20–50mm wide and up to 500mm long and probably formed by the stretching of pillow crusts as lava was continually forced into the pillow tube (Snyder & Fraser 1963; Yamagashi 1985). Many pillow surfaces also display a ropy lava texture, or the bread-crust texture of Krakatau-type volcanic bombs produced by the rapid cooling and subsequent shrinking of the pillow surface (Fuller 1932).

Many pillows are hollow and contain within them features that allude to the complex and varied nature of pillow formation. Inner pillow surfaces may be smooth and glassy, indicating quenching due to water invasion immediately following the evacuation of lava (Fuller 1931; Moore et al. 1973). Small inward-protruding ridges (≤20mm wide, ≤200mm long) parallel to spreading cracks in the outer surface of a pillow also have quenched textures, probably due to rapid chilling by water entering new cracks during pillow growth. Lava flow features within hollow pillows include stalactites, lava tongues and lava benches. Short (<20mm) irregularly shaped stalactites with sharp protrusions and small, drip-like bulbous ends formed after the main flow of lava through a pillow had ceased. Congealed lobate lava tongues (Fig. 8) represent the final flow of lava through a pillow tube after its lava source was exhausted or blocked, or revival of lava flow within an earlier formed pillow tube (Moore et al. 1973). Stacked pancake-like lava benches formed when several pulses of lava flowed through a pillow. These are good geopetal structures as their flat lower surfaces indicate the horizontal plane at the time of pillow formation (Waters 1960). All these features have unquenched surfaces suggesting that water did not invade these pillow tubes immediately after they were emptied of lava.

Small (≤5mm) spherical and sub-spherical vesicles are scattered throughout the pillow lava and may account for up to 5% of the volume of the rock. These are most common towards the upper, outer edge of each pillow, indicating that when pillows reached their resting place they were sufficiently fluid to allow gas bubbles to rise (Moore et al. 1973).

Individual pillows display graduated changes in petrographic, compositional and microscopic textural characteristics. These changes record a cooling gradient resulting from rapid quenching as the lava erupted into water (Kawachi & Pringle 1988).

Fig. 7. Longitudinal and transfer spreading cracks in a pillow lobe surrounded by hyaloclastite, western headland of Dinghy Cove.

Fig. 8. Congealed lava tongue overlying a lava bench in the hollow tube of a drained pillow lobe, western headland, Dinghy Cove. Note the tiny lava stalactites extending from the irregular surface of the roof above the lava tongue, and the hyaloclastite that completely encloses this particular pillow.

Changes in crystallinity, grain size, and the number of minerals present can be used to define three major concentric bands in each pillow:

- the outer glassy margin forms a shiny black crust (≤5mm thick) composed of basaltic glass with fine perlitic fractures characteristic of rapidly quenched lava (Carlisle 1963; Moore et al. 1973). A few euhedral plagioclase and olivine crystals are present, and probably represent crystals formed within the magma chamber prior to eruption–they lack reaction coronas or extensive corrosion. The degree of crystallinity increases gradually from about 20% at the outer pillow edge, inwards to 40% bordering the spherulitic zone (Fig. 9);
- the spherulitic zone (≤20mm thick) is transi-

tional between the pillow margin and the core of the pillow. It begins with the appearance of opaque acicular, or needle-shaped crystallites which gradually increase in number until the entire glass groundmass has been replaced. Many are concentrated around the edges of pre-existing crystals, particularly feldspar. They also commonly form small (≤0.02mm) spherulites and dendritic inclusions within feldspar grains and glass. Towards the centre of the spherulitic zone, feldspar begins to appear in the groundmass as tiny (≤0.25mm), curved and whispy crystals. Similar to the outer layer, plagioclase and olivine microphenocrysts are present. Small (2–3mm diameter) soft mineral cubes are probably palagonite (Fig. 9); and

- the pillow centre is a dark grey, fine-grained alkali basalt. It begins with the appearance of pyroxene, which accompanies olivine, plagioclase, augite and magnetite to form an aphanitic groundmass which supports occasional microphenocrysts (≈1mm) of olivine and plagioclase. Although the inner core is essentially crystalline, the groundmass locally contains up to 5% glass.

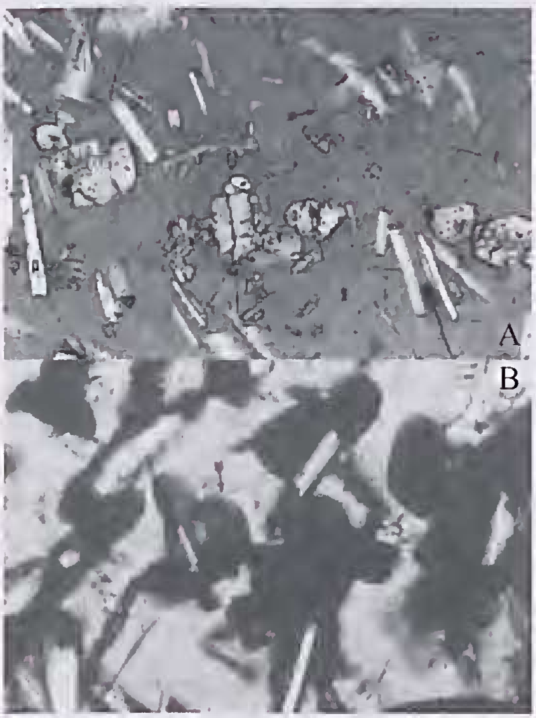


Fig. 9. A: Outer glassy margin of a pillow (Dinghy Cove). The basaltic glass (g) is altered to palagonite and contains well formed crystals of plagioclase (p) and olivine (o). Arrow indicates perlitic fractures. PPL; Field of view 20mm.

B: The spherulitic zone begins with the appearance of opaque crystallites, seen here to form dark spherulitic clusters (arrow) in the basaltic glass. Pale elongate crystals are plagioclase. PPL; Field of view 6.5mm.

Many pillows exposed in the cliffs of Lady Julia Percy Island display two sets of these concentric bands formed as a result of repeated quenching as water entered the inner tube of the pillow through cracks or joints after successive lava pulses (Moore et al. 1973; Snyder & Fraser 1963).

Hyaloclastite. Hyaloclastite is a submarine volcaniclastic sediment formed by the non-explosive quench fragmentation of chilled glassy outer pillow rims in cool water (McPhie et al. 1993). At Lady Julia Percy Island hyaloclastite occurs to the north of Square Reef and Cairn 2, but is best exposed in the cliffs around the headlands of Dinghy Cove where it forms a substantial proportion (≤30%) of the total volume of the subaqueous volcanic pile.

Hyaloclastite is composed of fragments of the glassy outer chilled margins of pillows with minor small (≤5mm), angular crystalline basalt fragments similar to pillow centres. Palagonite coats most fragments and forms the matrix of the deposit. Hyaloclastite is intimately associated with the pillows. The morphology of hyaloclastite fragments and the structure of the deposit as a whole are related to the distance from the source pillows from which fragments have been displaced.

Within 100mm of the edges of pillow lobes hyaloclastite is a massive, poorly sorted and grain supported (≤80%) deposit. Fragments range from coarse ash and lapilli to minor larger fragments (10–20mm diameter). Smaller fragments are highly angular, and characteristically display smooth, concave faces due to parting along conchoidal fractures. Larger fragments have highly irregular shapes and are often preserved in situ, close to–or partly attached to–the chilled margin of the pillow from which they were derived. Many display a jig-saw type fit with adjacent fragments. This suggests that as the hyaloclastite formed, it was covered quickly by subsequently formed pillows and protected from displacement or erosion. Displacement of fragments from their source pillow was probably mostly caused by the continued formation of hyaloclastite below, or the expansion of the pillow from which the fragments were formed. With greater distance from the pillow margins hyaloclastite becomes increasingly matrix supported (≤50%), and fragments become smaller and more rounded. The morphology of the distal fragments may have resulted from reworking and redeposition processes, or reflect the presence of perlitic fractures in

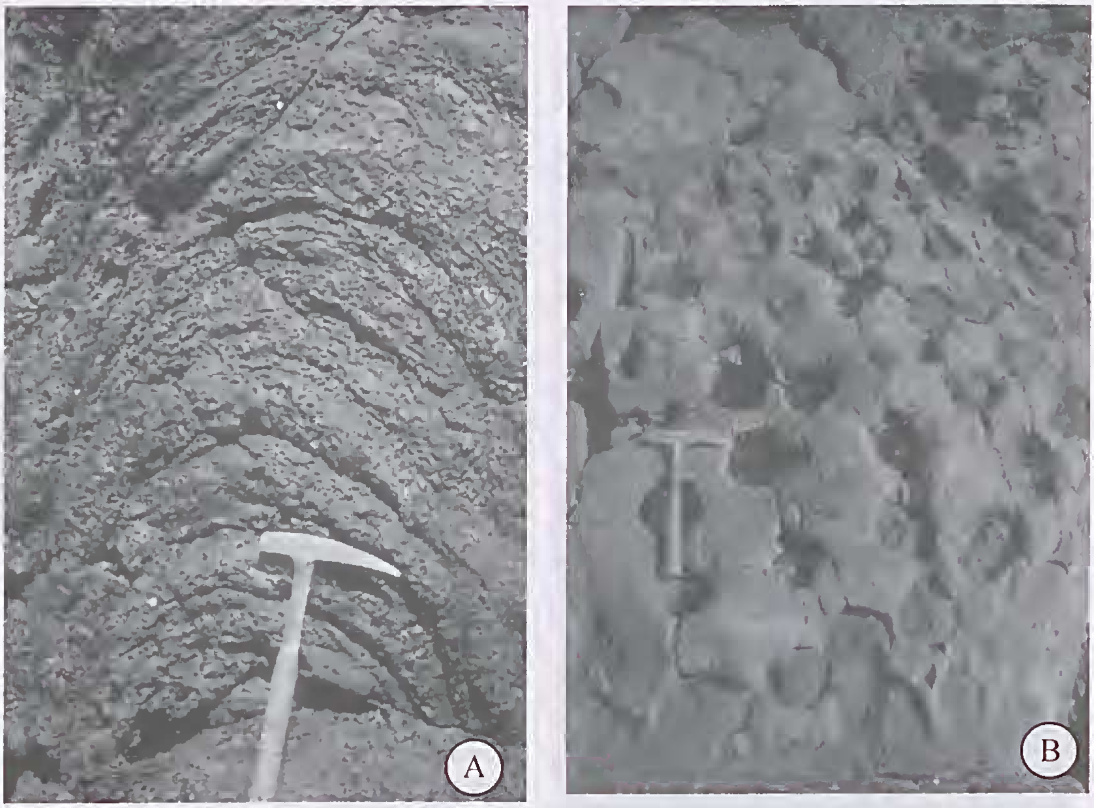


Fig. 10. Some features of the Pahoehoe lava flow, McCoy Platform. A: Ropy lava textures common to Hawaiian-type pahoehoe lavas and; B: Vertical pipe vesicles.

the basaltic glass from which they are derived.

In several places around the island hyaloclastite is bedded. High in cliffs west of Dinghy Cove inaccessible hyaloclastite beds dip at the same angle and direction as nearby pillows, but are truncated to the east by massive hyaloclastite. This bedding may represent redeposition by slumping shortly after formation (Smith & Batiza 1989). Elsewhere, hyaloclastite forms a bedded lapilli deposit. This deposit is thickest at Seal Bay (≤2m) where it is intimately associated with pillow lavas, enclosing several pillows and filling cracks in their surfaces. In places it has been compressed by overlying lava and squeezed upward into gaps between overlying pillows. Beds are up to 50mm thick, are well sorted and fine upwards, and indicate significant reworking and deposition, possibly by wave action in shallow water (Honnorez & Kirst 1975; Smith & Batiza 1989).

Pahoehoe flow. The subaqueous deposit grades into, and is capped by a single alkali basalt pahoehoe flow. This contact marks the transition from subaqueous to shallow water and subaerial volcanism, and therefore marks the approximate sea level at the time of eruption. The textural and morphological changes from pillows to pahoehoe resulted from a change in the environment into which the lava from the first eruptive phase flowed—from below sea level to close to, or above the sea surface—as the volcanic edifice grew. As such, there is no soil or obvious erosional features at this boundary. The upper flow lies directly upon friable and uncemented (therefore easily eroded) hyaloclastite that shows no evidence for redeposition and reworking, indicating that it was covered and protected shortly after it was formed.

The contact is quite irregular, often difficult to distinguish, and dips gently (0.3°) southeast, from about 15m (Dinghy Cove) to 3m (Thunder Point) above sea level. The flow ranges from 0.5m thick at Dinghy Cove where it overlies pillow lava and hyaloclastite, to 3m thick at Thunder Point where it fills a depression in the surface of the subaqueous deposit. The base of the flow is slightly glassy and marked by a thin parting (≈20mm thick) indicating rapid cooling. Geopetal surfaces–secondary carbonate deposits within gas voids in the flow–show that the island has tilted at least 4° to the southeast since their formation, suggesting the initial surface of this flow probably sloped to the north. This indicates that the flow probably originated from the same submerged vent that sourced the pillow magmas.

The flow is best exposed as the surface of McCoy Platform. Here its base conforms to the upward-convex shape of the underlying pillows. Volcanic features typical of Hawaiian-type lava flows not commonly seen in Victorian mainland lavas are spectacularly well preserved here (Fig 10). Ropy surface textures are common, and consist of numerous parallel corrugations which run across flow tongues, and are deformed convexly towards the direction of flow. In the centre of McCoy Platform numerous vertical pipe vesicles, up to 100mm in diameter, probably formed prior to solidification in a stationary lava pond which filled a hollow in the surface of the underlying pillow deposit.

The internal structure of the flow is well exposed at Thunder Point where it is comprises numerous ~300mm thick subhorizontal flows, each separated by a thin horizontal parting. Each flow is characterised by a well developed distributary tube system (Fig.11):

- the upper 10–20mm is a dense lava with minor spherical vesicles (1%), grading downward into a 50–100mm thick, highly vesiculated (50–60%) lava;
- the centre of each layer features small lava tubes with irregularly shaped, upward arched roofs and flat floors. The tubes are about 100–150mm high, up to 500mm wide, and some are wholly or partially infilled by secondary carbonate material. Tubes run parallel to each other along the centre of each flow, and are separated by thin walls of vesicular lava; and
- the floor of the lava tubes is 50–100mm thick and highly vesicular, grading downwards to a thin (10–20mm) dense lava base.

Each thin layer represents a pulse of highly gaseous lava. The highly irregular shape and rough, vesiculated walls of the openings in the pahoehoe flows indicate that they are gas blisters formed by coalescence of adjacent vesicles in the centre of each flow unit, which causes the flow to part. Concentric layers with differing vesicle size and abundance are caused by shearing as the lava flows after it has begun to cool and solidify (McPhie et al. 1993).

Fig. 11. Internal structure of pahoehoe flow, Thunder Point. Note the distributary tube system within each thin flow. The tube in the lower right corner has a false lava base and secondary carbonate has begun to fill the tube to the top left.

Lava globules. The pahoehoe flow is a fine grained crystalline lava composed mainly of plagioclase, olivine and pyroxene, and a minor amount of interstitial glass similar to, although slightly coarser than, the inner pillow lavas. However, a unique feature of this flow is numerous small (≈5mm) subrounded to rounded, irregular and ellipsoidal dark grey lava globules and globule aggregates (≤15mm), many of which contain a sub-spherical void or vesicle. These are scattered randomly throughout the less vesicular portions of the flow where they locally form up to 50%, although mostly less than 25%, of the lava. These globules represent a late stage melt that is slightly more fractionated than the general host rock (see analyses by Edwards 1994), and preserve a volcanic texture that has not been recorded elsewhere in the Victorian Newer Volcanic lava fields.

The globular textures are probably the result of a more volatile-rich residual magma formed during the low-pressure (near surface) crystallisation of the alkali basalt. They indicate that the magma experienced decompression during its ascent towards the surface, forming melt-separates and vesicles. The spherical globules at McCoy Platform are crystalline masses of radiating elongate (1–2mm) crystals of andesine, sanidine, augite, ilmenite, and minor olivine. The globule margins are sharp and clearly defined by a rim of small (0.1–0.2mm) plagioclase and augite crystals, which indicate that the host lava had essentially crystallised and stopped flowing prior to the introduction of the residual material which subsequently filled gas vesicles. Unlike the host rock the globules contain little olivine, an early formed mineral in these lavas, but a significant amount of late-crystallising ilmenite. The lack of typical hydrous, late crystallising minerals such as amphibole

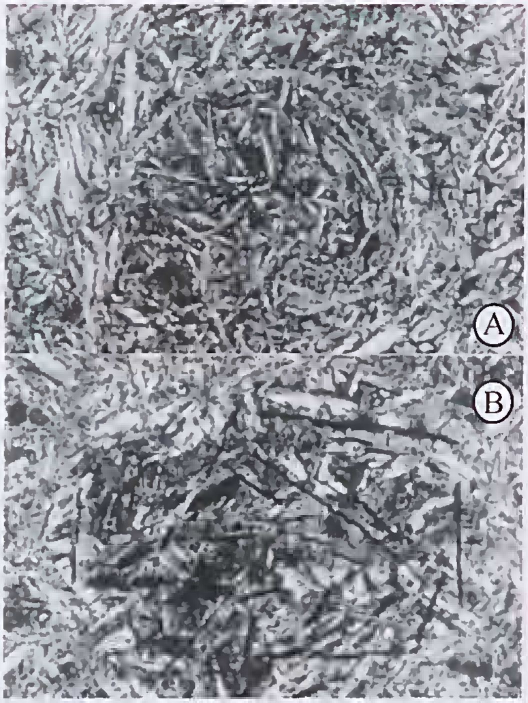
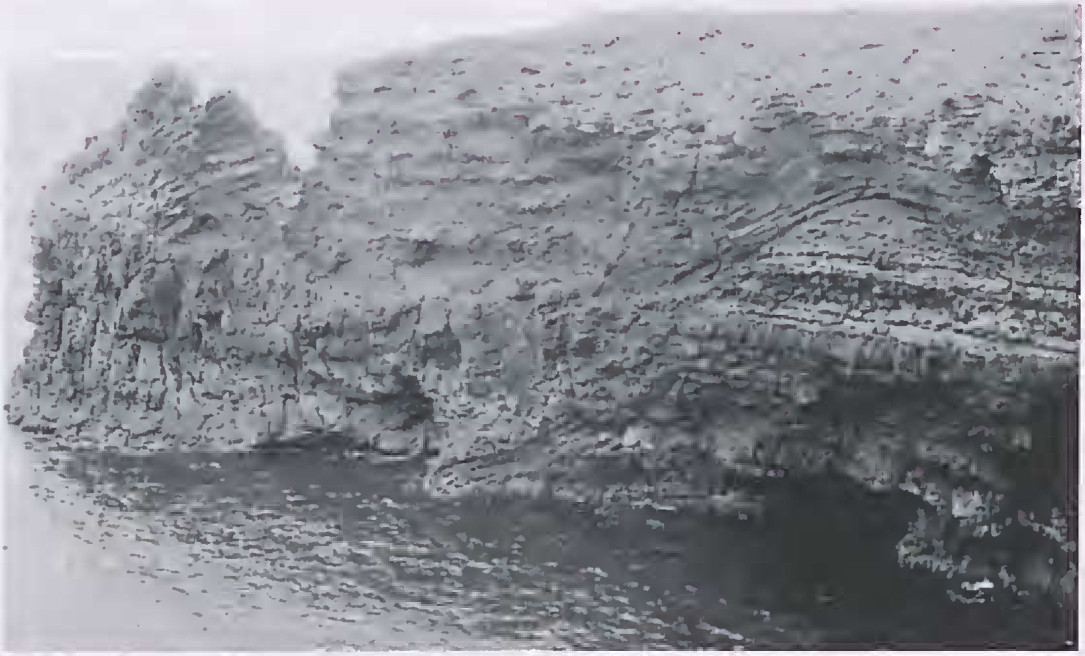


Fig. 12. Globules in the pahoehoe lava. A: Almost spherical globule with a well defined rim of plagioclase and augite crystals. Note the higher concentration of late-crystallising ilmenite within the globule. (Dinghy Cove) PPL; Field of view 40mm. B: Emulsion-like globule with elongated pyroxene (a) and ilmenite (i). Note the coarser grain size of the globule compared to that of the host lava. (McCoy Platform) Cross polars; Field of view 20mm.

suggests that the globule melt was not H_2O-rich, but never-the-less, the larger grain size of most globules relative to the host rock suggests that there was a significantly higher volatile concentration within the crystallising globule magma compared with the parent magma. Rapid crystallisation of such volatile-rich magma can explain the relatively coarse mineral grains and quench-like textures. In contrast, at Dinghy Cove globules form emulsion-like textures with interlocking crystal edges with the finer grained host rock. Internal foliation (crystals parallel to the globule boundaries) and curved plagioclase crystals indicate flow during crystallisation (Fig. 12). These textures demonstrate that the globules are primary volcanic features. They were formed from residual material that was present prior to the complete solidification of the host magma.

The second phase of volcanism

Subaerial volcanic activity followed the earlier predominantly subaqueous eruptions. This second phase of volcanism erupted from a different vent, now exposed at Pinnacle Point and within Horseshoe Bay on the southwestern edge of the island (Fig. 13). There is no significant erosion and no soil is developed on the surface of the pahoehoe flow. In many



environments this might indicate that little time elapsed between the two volcanic phases. However, given the extremely exposed nature of island to the erosive forces of the Southern Ocean environment, it is probable that any weathered material was rapidly blown or washed away, maintaining a fresh upper surface on the pahoehoe flow. The subaerial sequence is about 15m thick and began explosively, forming a small pyroclastic flow deposit. This was followed by quiet effusion of flat-lying plains-type lava flows, and terminated with lava fountaining which produced vitric ash. Although these volcanic features are relatively small, cliff exposures provide a unique opportunity to examine a section through the centre of a volcanic vent, and in places, provide insights into how pyroclastic flows and plains-type lava flows develop.

Pyroclastic flows. The small volcaniclastic deposit is centred around Pinnacle Point, and is exposed in the cliffs along the southwest of the island, approximately 20m above sea level. It extends less than 400m from the vent. It has a maximum thickness of 8–10m at Pinnacle Point but thins rapidly to 2–3m at Thunder Point, and to only a few centimetres thick beyond there. Close to Pinnacle Point this pyroclastic deposit is truncated by overlying subaerial lava flows.

Although the gross morphology of this deposit is similar to that of the maar rims common to the western volcanic district, it does not exhibit the usual characteristics of a phreatomagmatic tuff-producing eruption. Fine grained material makes up a relatively small proportion of the deposit, and there is very little air-fall planar bedding or base surge cross-bedding. A high proportion of large basalt blocks, reverse grading, and the lack of sag structures (Cas & Wright 1988) indicates formation as a pyroclastic flow deposit. The volcaniclastic debris flowed along the surface as a result of the rapid collapse of a small, dense eruption column which reached only a short distance above the vent (Cas & Wright 1988) — essentially a sputtering, or boiling event.

This deposit is only accessible in the eastern

Fig. 13. Volcanic vent at Pinnacle Point, viewed across Horseshoe Bay from Thunder Point. This vent intrudes pillow lavas from earlier submarine volcanic eruptions (bottom-right). The first eruption produced pyroclastic flows (light material middle-right), subsequently truncated by plains-type lava flows seen draped over them at angles of up to 30°. What remains of the throat of the vent is now filled with massive columnar-jointed basalt (bottom-left). The thinly bedded lava and scoriaceous layers (upper-left) at the top of the pinnacle fused to form the clastogenic flows that cap the southern portion of the island.

Fig. 14. Pyroclastic flow exposed in cliffs at Thunder Point (see also Fig. 13). The pick lies against the middle section of flow unit. Notice the upward increasing percentage of large basalt blocks. There is a sharp transition to the top section that is thinly bedded and much finer grained.

headland cliffs of Horseshoe Bay, where it is composed of two pyroclastic flows (Fig. 14). Each flow consists of three units distinguished by differing textural and structural characteristics:

- the basal layer (100–200mm thick) is composed of planar beds which conform to the flat-lying lava below and are laterally continuous to the edge of the deposit. In Horseshoe Bay they dip steeply (45–55°) to the base of Pinnacle Point. Beds are up to 50mm thick, fine upwards, and are composed of mainly small (1–2mm) clasts. Successive beds are generally composed of coarser fragments which ultimately grade into the coarser middle section of the flow. The basal layer represents the initial surge of fine-grained material along the surface from the vent in front of the main body of the flow.
- the middle layer forms the bulk of each pyroclastic flow and dips shallowly (5°) away from the vent. At Thunder Point it is about 1.0m thick but thins rapidly from here and cannot be traced beyond the headlands of Horseshoe Bay. It is massive and highly unsorted, with grainsize ranging from fine ash (≤1mm) to large basalt blocks (≤800mm). It contains about 70% clasts which vary from angular blocks, to rounded bombs, and highly irregular grains. Clasts are texturally variable, ranging from highly vesicular and almost scoriaceous lava with ropy textures, to massive dense lava. Minor accessory lithics (≤1%) are carbonate sediments, probably Port Campbell Limestone or Gellibrand Marl country rock ejected during the eruption. These have been heated and recrystallised during the eruption, and have not retained original textures. Clasts are lightly bonded by a matrix composed of secondary clay minerals and minor altered basaltic glass. These materials thinly rim the clasts, making a large proportion of the de-

posit matrix supported. The most striking feature of the section is the reverse grading of the larger clasts. In general, larger fragments increase in average size towards the top of the section, while the finer grained population remains constant throughout the deposit. There is a sharp transition to the upper layer;

- the upper layer is fine grained (1–2mm) and generally less than 100mm thick. It fines upwards, and may be massive or display planar and minor cross bedding. This fine grained surge and air-fall material indicates that a cloud of fine ash accompanied the flow.

Subaerial lava flows. Pyroclastic activity was followed by relatively quiet subaerial effusion of five low-volume, thin (3–4m) plains-type alkali basalt flows which form the bulk of the upper portion of the island. Around Horseshoe Bay the flows truncate and thin over the top of the underlying pyroclastic deposit, but thicken from there and form the flat-lying surface of the island.

Excellent exposures near the vent at Pinnacle Point show that these flows have developed as numerous interbedded thin lava and scoriaceous bands, presumably short pulses in a single eruptive event, which fused to form a single flow. The remnant of an agglutinated spatter rampart forms a 2m high deposit at Thunder Point.

Each flow displays a characteristic sequence of textures. The lower half of each flow is characterised by dense lava with minor spherical vesicles (≤1%). This grades upwards into highly vesicular lava (50–60%), which in turn is overlain by scoriaceous rubble and lava spatter. Several flows display an irregular–possibly erosional–lower contact with the upper rubble layer of the flow below.

These lavas commonly display crude vertical jointing. Joints are generally most pronounced in the upper parts of each flow where cooling occurred more quickly. True columnar jointing is found only at the base of Pinnacle Point in part of the neck of the volcanic vent. Columns here are vertical.

Scoria and lava spatter. Final subaerial activity was an episode of lava fountaining from the same vent. At Thunder Point, the deposit is essentially a 2m high pile of fused scoriaceous fragments which may once have formed a cone or rampart around the vent. At Pinnacle Point, this deposit is an interbedded succession of thin lava flows and spatter layers (≤300mm), representing a series of clastogenic flows produced by the amalgamation of hot spatter fragments close to the vent. These flows did not move far and are interlayered with deposits of spatter which cooled too quickly to form a flow. Such layering probably reflects the pulsating nature typical of such eruptions. The top and bottom of each lava flow is welded strongly to fragments above and below. Further from Pinnacle Point the layers are fused into a single lava flow. The edge of this deposit forms a geomorphologically prominent ridge across the island close to Horseshoe Bay.

Vitric ash. Vitric ash deposits are preserved in small patches distal to the scoria material scattered along the top of the northern cliffs between Cape Frederick and Sphinx Head. These conformably overly the uppermost lava flows, but are largely concealed by soil. Where exposed the ash is highly weathered and friable, never greater than 400mm thick, and forms sub-horizontal beds 60–80mm thick. It is composed mainly of highly altered basaltic glass with tiny scattered crystals that may be plagioclase, and augite or olivine. Minor highly vesicular basaltic lithics and scattered cuspate shards of uncrystallised volcanic glass are also present. The latter are possibly fragmented walls of vesicles and indicate an explosive magmatic eruptive genesis (Heiken, 1974), derived either from the final eruption on the island or from the air-fall component of a phreatomagmatic eruption on the nearby mainland.

GEOCHRONOLOGY

The pillow lavas were considered unsuitable for dating due to the likelihood of excessive radiogenic argon trapped in the rapidly quenched volcanic glass, and the upper subaerial lava flows were too altered. However, two samples, one from each of the identified volcanic phases, were suitable for total rock potassium/argon (K/Ar) dating by Amdel Limited, South Australia (Appendix 2):

- Pahoehoe lava immediately above the pillows at Dinghy Cove yielded an age of 7.80 ± 0.08 Ma. This age represents the youngest preserved product from the first volcanic phase from a vent which lies submerged somewhere to the south of the island.
- A dense basalt block from the pyroclastic flow at Thunder Point revealed an age of 6.22 ± 0.06 Ma. This age represents rocks produced close to the end of the second volcanic phase from the vent exposed at Pinnacle Point on the southwest coast of the island.

Ancient Sea LevelMarkers	Locality	Height (+/- sea level)
shore platform	McCoy Platform	+18m
pillow/pahoehoe contact	cliffs around the island	to 15m
erosional indentation	cliffs around the island	+10m
shore platforms	Thunder Point and Pinnacle Point	+3m
boulder beach	near Delta Reef	+3m
sea caves	Fern and Seal caves at Seal Bay	+1.5m
sea caves	Horseshoe Bay, and Thunder Point to Delta Reef	0m and +3m
submerged platform	West Cape	-5m
submerged platform	Cape Frederick	-14.5m
submerged platform	Seal Bay	-16 to -18m
submerged platform	Delta Reef	-25 to -27m

Table 1 Summary of the geological and geomorphological ancient sea level markers preserved at Lady Julia Percy Island.

The volcanic rocks of Lady Julia Percy Island are thus Late Miocene in age, and were produced during two discrete phases of volcanic activity approximately 1.6 Ma apart. These ages are significantly older than commonly quoted maximum ages for Newer Volcanics in the Western District Province of Victoria.

Significance of the geochronology

The Western District Province is generally regarded as a relatively young phenomenon, with quoted ages ranging from a few thousand years, mainly for young scoria cones, to a maximum of around 3–4.6 Ma for the more extensive plains lava flows (McDougall et al., 1966; King, 1985; Joyce, 1988; Price et al., 2003).

The 6–7 Ma age for Lady Julia Percy Island is not unique to the Newer Volcanic series, although most ages comparable to this have previously been obtained from west-central Victoria. Such rocks were grouped separately, due to their apparently earlier age and their different rock associations (eg. volcanics of the Central Highlands Sub-province and the trachyte–basalt association of the Macedon–Trentham Province; Price et al. 2003). Wallace (1990) has proposed that, based on a study of 61 K/Ar dates, the Newer Volcanics of the Western District region can be subdivided into several distinct groups based on eruption age. His oldest group (Group 1) includes ages ranging from 5.83–7.1 Ma. Even earlier volcanic activity may have occurred at 8–8.5 Ma, as evidenced by a zircon fission-track age peak around 8.4 Ma recorded from locally-sourced Stony Creek Basin sediments at Daylesford (K. Sniderman & P. O'Sullivan pers comm. in Willman et al. 2002).

The results obtained from Lady Julia Percy Island add to a growing collection of recent data that show the maximum age of the Newer Volcanics series within the central and southern portions of the Western District Province is significantly older than previously suggested. For example, olivine basalt from the Newer Volcanic lava plains just east of Ararat has a K/Ar age of 6.07± 0.11 Ma (Cayley et al. 1995). The Ararat example lies well within the Western District Province. It overlies approximately 70m of even older basalt flows, indicating that the lava plains were already well established in the Western District Province by the Late Miocene (Cayley & McDonald 1995). The Ararat data and the new geochronology for Lady Julia Percy Island indicates that eruption centres and basalt flows with ages well in excess of 5 Ma (Late Miocene) are widely distributed in Western District Province.

This conclusion seems at odds with the current widely accepted impression of a considerably younger age for the Western District Province compared with other parts of the Newer Volcanics series (eg. Price et al. 2003). This impression has grown from the many published radiometric dates that are in the range of several thousands to 3–4 million years (eg. McDougall et al. 1966; Wellman 1974; Day 1989). These are mostly from the intact volcanic edifices and related flows that rise above—and rest upon—

much more extensive lava flows. Sampling has necessarily been largely restricted to the fresher, younger surface features of plain (eg. Gill 1978; Stone et al. 1997), introducing a young-age bias to ages published for the Newer Volcanics of the Western District Province. Dates obtained for older lava flows are less common and are less widely distributed geographically (eg. King, 1985). Even where older flows are exposed, they are typically deeply weathered and unsuitable for conventional dating techniques.

Lady Julia Percy Island offers a rare opportunity to observe and sample some of the oldest and best preserved Newer Volcanic rocks in the Western District Province. Its island geography has enabled it to remain isolated and protected from burial by younger lava flows. Moreover, fresh rock is continuously exposed as a result of rapid coastal erosion. Therefore, although the 6–7 Ma ages obtained for the sequence on the island are older than those commonly published for this region, they are entirely consistent with other recent geochronology from the Western District Province, and with the known and expected age range of the Newer Volcanics series in Victoria as a whole.

ANCIENT SEA LEVEL MARKERS

In the Tyrendarra Embayment, Cainozoic eustatic oscillations are recorded by the depositional sequence of marine and fluvial sediments. The 6.22–7.80 Ma age of the Lady Julia Percy Island lavas place their eruption at some time during the regression of the sea from the area, prior to the transition from limestone deposition to that of the fluvial sediments (Hanson Plain Sand) which overlie the Port Campbell limestone onshore, and underlie much of the Newer Volcanic Plain of Victoria (Tickell et al. 1992).

Several ancient sea levels are recorded in the cliffs of Lady Julia Percy Island. The only non-erosive marker is that of the subaqueous/subaerial lava flow contact. As the formation of pillows depends upon many factors, including lava extrusion rate and water confining pressure (Yamagashi 1985), this boundary only approximates relative sea level at the time that pillow formation ceased. Today it lies 15m above sea level, indicating that at about 7Ma the sea surface was probably some metres higher than present. Just how much higher is problematic, as there is no preserved record of the effect of vertical movements due to processes such as post-eruptive subsidence or tectonic uplift. Evidence for a previous sea level at +15m is not widely recognised along nearby mainland coasts, although some erosional features at +12 to +15m have been noted in the headlands of Portland Promontory (Boutakoff 1963). However, unlike erosional sea level markers, and irrespective of the absolute sea level, this marker probably represents nothing more than a transient sea level during the eruption of a lava flow, rather than one maintained for a significant period of time.

In addition there are several geomorphic ancient sea level markers preserved at different levels both above and below present-day sea level at Lady Julia Percy Island, and include sea caves and wave-cut platforms (Table 1). These are the result of erosive modification of the volcanic pile subsequent to its eruption. One such feature—a prominent indentation in the cliffs approximately 10m above sea level—is inferred from offshore photographs of the island. It is most obvious within the pillow deposit close to Dinghy Cove. As this feature does not correspond to a geological boundary, and cuts across the top of the pillow deposit into the subaerial flows, it is interpreted as the beginning of a wave-cut shoreline developed during a higher-than-present sea level.

Wave-cut platforms occur along the southern shores, reflecting present-day erosion at sea level where the strong prevailing winds form the most powerful waves. Other wave cut platforms and sea-caves are elevated at various heights above the present sea level. These are also mostly found in the cliffs of the southern headlands. The McCoy Platform at West Cape is the largest of these, and lies approximately 18m above the present sea level. Its surface displays the characteristic well developed pebble-worn potholes and rock pools, and honeycomb weathering textures typical of present-day Victorian wave-cut platforms. Bathymetric data also identifies several submerged platforms along the southern flank of the island. In contrast, a submerged bench adjacent to Cape Frederick has not been exposed to south-westerly waves and may therefore be a primary volcanic feature, possibly the edge of a lava flow.

At the southern edge of Delta Reef, an inaccessible boulder beach is preserved in the entrance of a sea cave approximately 3m above the present sea level. It is a 3–5m thick deposit composed of rounded basalt pebbles and boulders up to approximately 1m diameter, and similar in appearance to the present day beach deposits at Dinghy Cove and Seal Bay. The deposit is exposed as a vertical cliff section, and is therefore probably cemented by secondary minerals.

Coastal geomorphological features of the nearby mainland coast preserve ancient sea levels that are both higher and lower than present, and include numerous stranded beaches and shore platforms, and drowned river valleys along the coast between Port Fairy and Warrnambool. These are summarised in Edwards (1994). The most widespread evidence for an ancient sea level in this region is at +3m and includes sea terraces, cliffs and caves around Portland Promontory, and a shore platform cut into Miocene limestone at Two Mile Bay. The stranded boulder beach, and several stranded platforms and sea caves are preserved at this level on the island. However, together these represent an incomplete record of a complex succession of relative sea level rises and falls that have overlapped and been superimposed upon each other, in areas possibly with differing tectonic histories. In the absence of datable material and a detailed understanding of local tectonics, the Lady Julia Percy Island ancient sea level markers cannot be directly compared to any of the Holocene levels preserved on the nearby mainland, which limits their use at present.

CONCLUSION

Lady Julia Percy Island is one of the earliest known eruption centres of the Western District Province of the Newer Volcanic lava plains of Victoria. It offers a unique opportunity to observe a wide range of spectacular and well preserved volcanic structures, textures and relationships not found together elsewhere in Victoria.

Initial subaqueous deposits of well developed pillow lavas and associated hyaloclastites are the best deposits of their kind in Australia, and have preserved a fantastic array of the classic morphologies and textures seen forming in subaqueous lavas today. Of particular interest is the well exposed gradual transition from subaqueous to subaerial textures marking the sea level at the time of eruption. At this transition, pillow morphologies merge into pahoehoe lava—the well preserved internal structures of which provide important clues to the ways such flows propagate. This lava also displays an unusual texture of small lava globules. The globules are interpreted to have formed from late-stage residual magma filling vesicles just prior to complete solidification of the host magma.

Subsequent subaerial deposits of the second phase of volcanic activity were sourced from Pinnacle Point. Here, cliff faces provide a rare opportunity to examine the internal anatomy of a volcanic vent. Of special interest are the internal structures of reversely graded pyroclastic flows, subaerial lavas and several clastogenic flows, all of which demonstrate aspects of how these volcanic features developed.

The spectacular exposures of volcanic features are maintained by the unrelenting erosion of coastal cliffs. Lady Julia Percy's island geography has also protected it from burial by younger lavas, which on the nearby mainland have thickly covered the majority of the earliest New Volcanic features. The 6.2–7.9 Ma ages for Lady Julia Percy Island, in conjunction with recent radiometric ages for other Newer Volcanic eruptions in the onshore part of the Western District Province, support the contention that the present subdivision of the Western District lava plains into several provinces on the basis of age (and/or compositional differences; Price et al., 2003) may reflect an incomplete geochronological dataset across the region rather than significant differences in the age of volcanic activity.

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APPENDIX 1

Selected total rock X-ray fluorescence analyses of Lady Julia Percy Island lavas.

	1	2	3	4	5	6	7	
SiO_2	47.50	47.91	48.34	50.38	48.05	48.46	48.89	**SiO_2**
TiO_2	2.06	2.06	2.12	1.84	2.15	2.05	2.28	**TiO_2**
Al_2O_3	13.43	13.84	13.76	14.43	13.68	13.60	13.79	**Al_2O_3**
Fe_2O_3	13.26	11.58	12.69	12.20	13.15	12.16	12.34	**Fe_2O_3**
MnO	0.17	0.15	0.17	0.13	0.16	0.17	0.16	**MnO**
MgO	8.65	8.54	8.20	6.85	8.66	8.66	7.43	**MgO**
CaO	8.22	9.04	8.49	8.49	8.31	8.31	8.32	**CaO**
Na_2O	3.48	3.61	3.62	3.62	3.85	3.34	3.77	**Na_2O**
K_2O	1.49	1.31	1.56	1.14	1.61	1.47	1.64	**K_2O**
P_2O_5	0.51	0.51	0.53	0.40	0.55	0.49	0.57	**P_2O_5**
SO_3	936	551	182	185	207	333	290	**SO_3**
Cl	836	1824	900	383	574	402	1178	**Cl**
Cr	243	223	217	257	239	223	180	**Cr**
Ba	404	384	393	285	414	331	396	**Ba**
Sc	14	20	20	25	20	21	20	**Sc**
Ce	72	55	53	66	74	44	84	**Ce**
Nd	22	51	37	60	29	49	28	**Nd**
V	173	176	171	174	165	168	174	**V**
Co	45	48	49	57	43	51	47	**Co**
Cu	97	54	97	100	84	71	62	**Cu**
Zn	124	119	133	131	129	117	135	**Zn**
Ni	178	185	183	198	219	275	175	**Ni**
Ga	20	21	21	16	22	19	21	**Ga**
Zr	176	186	181	159	190	182	191	**Zr**
Y	21	22	23	28	23	20	27	**Y**
Sr	592	623	595	498	655	582	600	**Sr**
Rb	32	28	32	24	32	29	34	**Rb**
Nb	38	39	41	28	42	37	44	**Nb**
Th	5	6	2	9	5	3	4	**Th**
Pb	8	6	4	13	6	8	4	**Pb**
As	0	6	3	-6	0	-2	0	**As**
Mo	5	1	2	-1	4	0	3	**Mo**
U	0	1	3	1	0	0	0	**U**
Loss	0.01	1.37	0.30	0.26	-0.35	1.15	0.27	**Loss**
Total	**99.17**	**100.38**	**100.10**	**100.02**	**100.15**	**100.15**	**99.81**	**Total**

Samples:

1. Outer chilled margin of a pillow, Dinghy Cove (AMG 585788–5747300).
2. Centre of a pillow, Dinghy Cove (AMG 585788–5747300.
3. Pahoehoe lava flow, Dinghy Cove (AMG 587890–5747830).
4. Pahoehoe lava flow, McCoy Platform (AMG 58665–5747150).
5. Lava block from pyroclastic flow, Thunder Point (AMG 587000–5746390).
6. Subaerial lava flow, Dinghy Cove (AMG 587900–5747800).
7. Subaerial lava flow, Pinnacle Point (AMG 58685–5746550).

APPENDIX 2

Potassium–Argon analyses.

Sample	%K∅	^{40}Ar*(×10–^{11}moles/g)	^{40}Ar*/ ^{40}Ar$_{Total}$	Age#
Pahochoe flow, final product of the first phase of volcanism, 15,5m above sea level, sea cliffs, Dinghy Cove. (AMGω 587890–5747830)	1.3557 1.3577	1.8395	0.812	7.80 ± 0.08
Lava block from pyroclastic flow, second phase of volcanism, 21m above sea level, sea cliffs, Thunder Point (AMG 587000–5746390)	1.328 1.330	1.4368	0.609	6.22 ± 0.06

∅ Mean K value is used in the age calculation.
* Radiogenic ^{40}Ar.
\# Age in Ma—error limits for analytical uncertainty at one standard deviation.
ω Co-ordinate system AGD 66.

Constants: ^{40}Ar = 0.01167 atom %
$\lambda\beta$ = 4.962 × 10–^{10}y–^{1}
$\lambda\epsilon$ = 0.581 × 10–^{10}y–^{1}

Analyses conducted by Amdel Limited, Mineral Services Laboratory, South Australia, report numbers G8948/91 and G830100G/94.